A Resilience Enhancement Scheme of Cyber-Physical Power System for Extreme Natural Disasters

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***Abstract*—Extreme disasters seriously threaten power system security and stable operation. Power system resilience is an important means to evaluate the system response to low probability and high impact events. This paper proposes a resilience enhancement strategy based on cyber physical power system to cope with extreme natural disasters and restore the power system. At first, a defense framework for natural disaster is given to show stages and techniques used in resilience enhancement strategy. Secondly, a zone division based power flow adjustment method is proposed to adjust the transmission power with high failure probability, which can reduce the risk of cascading failures. Finally, two resilience evaluation functions considering load restoration and equipment restoration are proposed respectively to guild collaborative communication lines and transmission lines restoration. Simulation results of the New England 39-bus test system demonstrate the effectiveness.**

Keywords—Cyber Physical System; Natural Disaster; Power System Restoration; Resilience Enhancement

I. INTRODUCTION

With the expansion of power system and the strengthening of interconnection, it is increasingly difficult to maintain the safe and stable operation of large power system under extreme disasters. In recent years, blackouts caused by extreme disasters have occurred all around the world, such as ice disaster in South China in 2008, hurricane Sandy in the United States in 2012, etc. Resilience of power system refers to the ability to maintain and restore normal functions in the face of severe accidents, extreme disasters or external attacks [1]. With the rapid development of cyber physical power system, the integration of information technology and power system is gradually deepening, which brings opportunities and challenges for the power system to maintain safe and stable operation under abnormal conditions [2]. Therefore, the research on the resilience of power system in the cyber physical environment is helpful to cope with low probability and high impact events, and improve the power system ability of prevention, resistance and disturbance absorption.

The research of power system resilience includes disaster resistance and rapid restoration after disaster. In view of the influence of natural disasters, a method is proposed to predict the fault probability of transmission lines by using meteorological and geographical data [3]. A risk-based islanding defense algorithm was proposed to cope with cascading effects in extreme weather [4]. Considering the influence of meteorology on renewable energy, a prediction model of recovery cost and power generation loss was established in [5]. A time-based ladder diagram resilience quantification method is proposed, and the concepts of operation resilience and infrastructure resilience are introduced [6]. But the above methods only evaluate the system resilience without restoration. Power system restoration has developed many optimization methods for restoration strategies using mathematical programming and evolutionary computation [7-9]. Reference [10] proposed a real-time restoration decision making method based on neural network, which effectively improved the restoration speed of the system. However, these restoration methods are not combined with the feature of cyber physical system. Cyber physical power system improves the flexibility, observability and controllability of power system [2]. Reference [11] proposed a dynamic team formation mechanism on the basis of information multi-agent system, which improved the quality of information rapid processing. How to improve the system's ability to deal with extreme disasters from the perspective of cyber physical system needs further research.

This paper proposes a resilience enhancement strategy for cyber physical power system under extreme natural disasters. Firstly, a power system disaster defense framework is constructed, which runs through the three stages of disaster prevention, disaster resistance and post disaster restoration. Then, the power system zone division method, branch active power adjustment method and cyber physical system collaborative restoration method are proposed for the three stages to enhance the resilience of power system. Finally, the IEEE New England 39-bus system is taken as an example to verify the effectiveness of the proposed method.

II. Defense Framework for Natural Disaster

The defense framework for natural disaster is constructed as the basis of resilience enhancement strategy. The framework divides the process into three stages, including disaster prevention, disaster resistance and post disaster restoration. In each stage, different methods are used to optimize the power system. In the cyber physical system, resilience enhancement methods based on information technology are used to improve the resilience of the power system in extreme disasters.

A. Disaster prevention

Disaster prevention mainly refers to making full use of the collected data and information to strengthen the system resilience before the disaster. On the one hand, the importance of equipment can be evaluated to arrange the strengthening task. On the other hand, the power grid is zoned according to the system topology. The data include electrical data, such as system topology and operation status, and non-electrical data, such as weather forecast data and geographic information data.

The basic link of predictive protection is to identify the operation state of power system through situation awareness of cyber physical system. The data needed for situation awareness includes real-time online data such as generation power and load obtained through power grid data acquisition system, as well as offline data such as equipment parameters, operation and maintenance information and power system topology. Load importance classification is the premise to ensure the priority of important loads and rapid restoration. Load change prediction in the disasters should be combined with big data to build corresponding model for analysis.

DC transmission system requires strong structure of receiving end system. After cascading failure of weak receiving end system, continuous commutation failure will easily lead to DC blocking, thus further deepening the impact of extreme disasters on power system. For most transmission corridors, the transmission distance is long which is vulnerable to natural disasters. DC transmission can be used as supply source for restoration, which can accelerate the progress of system restoration. In order to reduce the probability of DC transmission system blocking caused by natural disasters, a DC blocking judgment method based on deep learning technique is used to quickly search for high-risk cascading faults [12]. The power grid dynamic security risk assessment system obtains a unified assessment model of power angle, voltage security and frequency security by using historical data through offline training, and carries out dynamic security online assessment for future uncertain scenarios and expected accidents [13].

The impact of extreme natural disasters on power system is uncertain. The fault characteristics of transmission lines are related to extreme disaster intensity, geography and surrounding environment. The vulnerability model of transmission lines is constructed to describe the relationship between fault probability and various factors. Using meteorological data and geographic data, combined with equipment maintenance status and service life, the transmission line fault probability can be predicted to reduce the uncertainty of fault.

In order to avoid power outage caused by line disconnect, the existing line fault probability data should be fully used to zone the power system according to the degree of connectivity. During zoning, power balance should be maintained in each zone, high-risk lines should be avoided in zone. And there should be high connectivity between buses in the zone, so as to improve the integrity of the zone after disaster.

B. Disaster resistance

Disaster resistance mainly refers to using the real-time information and the availability of the existing structure of the power system, dynamically adjusting the structure and state of the power system, optimizing the power distribution and maintenance resource scheduling, so as to strengthen the ability of the power system to resist the disaster.

Transmission line disconnection will lead to system power imbalance, line overload and other problems, and even lead to system instability or cascading failure. According to the results of preventive zoning, the active power of branch can be adjusted to effectively alleviate the above problems. By adjusting the power of each generator, reducing the exchange of active power between the zones and strengthening the balance of energy supply and demand in the zone, the stability problems caused by power imbalance after fault can be reduced. Reducing the transmission power on the line with high fault probability can effectively reduce the risk of cascading failure caused by overload of other lines.

With the rapid development of Internet of things technology, the monitoring system of power system for equipment is also more perfect. The application of image recognition technology in transmission line monitoring can obtain the damage degree of equipment in time and provide data support for the maintenance work in restoration stage. The development of 5G technology provides a new scheme for resource regulation and management. The networking dispatching of generators, emergency rescue and other resources strengthens the flexibility of disaster response to ensure the power supply of important loads.

In the normal operation of the power system, the information collection and processing of electrical equipment and operation scheduling are completed by the dispatching center. In this case, the reliability of communication equipment is required to be high, and the impact of communication failure is serious. However, extreme disasters not only affect the transmission system, but also affect the communication system, so it is difficult to ensure the availability of equipment communication. With the development of edge computing technology, the device terminal also has a certain processing capacity. In order to improve the ability of power system to deal with communication failure in extreme disasters, the regional autonomy technology is proposed based on the edge computing ability of power system. When the transmission area loses the ability to communicate with the outside areas, the equipment in the area can operate autonomously based on the historical data and the communication between the devices in the area, based on the specific operation rules and edge computing technology. For the external system, the operation state of the area can be deduced according to the state data and operation rules before the communication failure in the area, so as to facilitate the fault repair.

C. Post disaster restoration

Post disaster restoration mainly refers to the dispatch of rescue resources and personnel for the damaged information and electrical equipment after the disaster, so as to realize the rapid restoration of load and the coordinated maintenance of power and communication equipment. In the restoration process, the appropriate restoration decision method can speed up the restoration process and reduce the loss of power outage.

With the rapid development of cyber physical power system, cyber system enhances the observability of physical system, and provides more flexible methods for power system restoration and operation. After natural disasters, through the detection of physical system by cyber system, the disaster situation of lines can be quickly obtained, and the maintenance efficiency of fault lines after disasters can be improved.

On the other hand, the cyber system will also be affected by natural disasters, resulting in information equipment can not be used. To solve this problem, it is necessary to take into account the restoration process of cyber system and power system, and carry out cyber physical collaborative restoration. For the communication fault area, the restoration scheme is selected according to the pre-fault state and line restoration priority. Restore communication equipment before restoring transmission lines or restore electricity directly. For the communication available area, priority should be given to transmission maintenance, and the maintenance efficiency can be improved with the help of information system. Through the parallel maintenance and complementary advantages of power and communication, the rapid restoration of the whole power grid information physical system is realized.

Power system restoration is a multi-objective, multi-stage, multi-variable and multi-constrained optimization problem with nonlinear and uncertainty. For the restoration model with analytic objective function, the traditional mathematical optimization method can quickly obtain the optimal solution of the function by using the gradient; while the evolutionary calculation can effectively deal with the problems difficult to be solved by the traditional mathematical optimization method in the restoration process without the limitation of the nature of the problem. Power system restoration process has strong uncertainty. The process of power system restoration is highly uncertain. Whether the restoration of line equipment is successful, the recovery time required, the uncertainty of distributed power output, etc., are all acquired along with the restoration process, and the pre-established restoration plan is difficult to meet the real-time requirements of restoration. Before the restoration process, the Monte Carlo tree search method is used to generate a variety of restoration schemes and evaluate them, which are used as training sets for neural networks training. In the restoration process, the power system restoration process and the power of distributed generation are taken as input. Considering various uncertain factors, the optimized restoration scheme is generated in a rolling way and the restoration operation is carried out step by step [10]. Machine learning is used to assist power system restoration, which ensures the global optimal and real-time decision-making in the restoration process, and can deal with the uncertainty of the restoration process and realize dynamic decision-making.

III. TECHNIQUES OF RESILIENCE ENHANCEMENT

A. Zone division and active power adjustment

The disconnection of high-power transmission lines will redistribute the power of the grid, and the power of some lines will exceed the rated value, which will lead to cascading failure and power outage. The power system is zoned according to the topology, and the active power is adjusted to enhance the power balance within the zone to improve the resistance of the entire system to the disconnection of the transmission line.

The following indicators are used for evaluation of power system zoning.

The failure probability index can be reflected by the average failure probability in the zone:

$$f_1 = \sum_i (k_1 \sum_j \frac{P_j}{n_i}) \quad j \in Zone_i \tag{1}$$

where, j is the line number; P_j is the failure probability of line j; i is the zone number, $Zone_i$ is the set of lines included in zone i; n_i is the total number of lines in zone i; k_1 is balance factor.

Topological connectivity refers to the ability to maintain connectivity after the branch is disconnected. The topology connectivity index can be reflected by the line failure probability, the number of power-loss buses :

$$f_2 = \sum_i (k_2 \sum_j P_j n_{\text{loss},j}) \quad j \in Zone_i \tag{2}$$

where, j is the line number; P_j is the failure probability of line j; $n_{\text{loss},j}$ is the number of nodes lost after line j is disconnected; k_2 is balance factor.

The generations and the loads in the zone should be matched. Active power matching index：

$$f_3 = \sum_i (k_3 \frac{P_{L,\max,i}}{1+P_{G,\max,i}} + k_3 \frac{P_{G,\min,i}}{1+P_{L,\min,i}}) \tag{3}$$

where, $P_{L,\max,i}$, $P_{L,\min,i}$ are the maximum and minimum load power of zone i respectively; $P_{G,\max,i}$, $P_{G,\min,i}$ are the maximum power and minimum stable power of the generator of partition i respectively; k_3 is balance factors.

To ensure the restoration schedule and the utilization of transmission lines, the number of partitions should be minimized. Number of zones index:

$$f_4 = k_4 n \tag{4}$$

where, n is the number of zones; k_4 is the balance factor.

Power system resilience is the ability of the system to withstand disasters. In order to comprehensively consider the above influencing factors, the resilience evaluation indicators are integrated:

$$f_{\text{zone}} = f_1 + f_2 + f_3 + f_4 \tag{5}$$

For practical applications, the influence of a certain index can be strengthened by adjusting different balance factors k_1 to k_4.

In order to reduce the impact of the disconnection of the tie line between the zones, the active power transmitted on the tie line should be reduced as much as possible. Considering the probability of line failure, the line with high failure probability should have smaller active transmission power. The objective function of active power adjustment :

$$f_{\text{power}} = \sum_{i \in L} P_i P_{\text{power},i} \tag{6}$$

where, f_{power} is the evaluation function of branch active power, L is the set of tie lines, P_i and $P_{\text{power},i}$ are the failure probability and transmission power of line i respectively.

B. Collaborative restoration

The cyber system enhances the observability of the physical system, and at the same time provides more flexible methods for power system restoration and other operations. After a natural disaster, the use of cyber system to detect physical system can improve the efficiency of repairing faulty lines. On the other hand, the cyber system itself will also be affected by natural disasters, resulting in the unavailability of information equipment. In response to this problem, considering the mutual influence of the cyber system and the electrical physical system, the restoration sequence of the two is optimized at the same time, that is, coordinated restoration. And post-disaster restoration process is comprehensively reflected through two aspects of load restoration and cyber-physical equipment restoration.

For the restoration of cyber and power system, the primary goal is to complete the restoration of the lost load, and the secondary goal is to restore the outage equipment of the cyber-physical system. Based on this, the objective function of cooperative restoration is established:

$$f_{\text{ld}} = \sum_{t=0}^{T} P_{\text{lost},t} \Delta t \tag{7}$$

$$f_{\text{eq}} = \sum_{t=0}^{T} N_{\text{lost},t} \tag{8}$$

where, f_{ld} is the lost load function; f_{eq} is the equipment outage function; T is the restoration completion time; $P_{\text{lost},t}$ and $N_{\text{lost},t}$ is the lost load and power line outage at time t; Δt is the unit time length.

During the restoration process, the load to be restored should be balanced with the generating capacity of the generator. The generator satisfies the constraint of active power output. The power of transmission line meets the upper limit constraint of power.

In terms of line repair, the repair process requires that the transmission lines and communication lines of the same line cannot be repaired at the same time. The maintenance time of the communication line is a fixed time. The maintenance time of the transmission line is related to the communication line status and line length.

IV. SIMULATIONS

The New England test system is taken as an example to illustrate the proposed method. And, the geographical location of the transmission line is readjusted, as shown in Fig. 1.

A. Zone division and active power adjustment

To simulate the effects of extreme disasters, typhoons are assumed to pass through the system. Relevant studies show that line failure probability is related to line length, distance from typhoon track and typhoon intensity. Based on the above factors, a set of line failure probabilities in this scenario is formed. The failure probability is plotted on the transmission line diagram, as shown in Fig. 1.

In the disaster scenario, the genetic algorithm is used to solve the zoning model. The results of bus zoning and power line zoning are obtained as shown in Fig. 1.

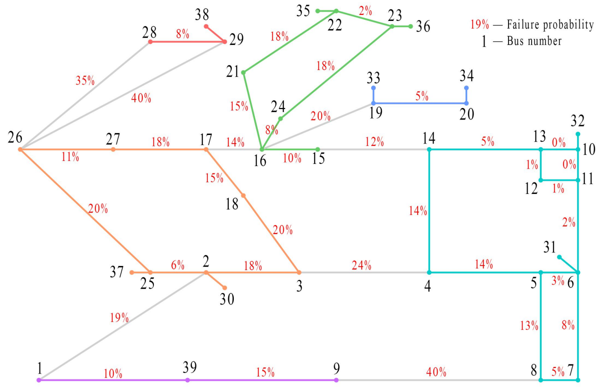

Figure 1. Zone Division Results

The optimization results show that each zone has compact structure. On the one hand, it can effectively resist the impact of the natural disaster that destroys the line, and ensure the availability of communication facilities; On the other hand, it is beneficial to maintain the convenience and rapidity of resource dispatching and accelerate the speed of power system restoration.

Based on the preventive zoning results, the generator output is adjusted according to the active branch adjustment method to reduce power transmission on the tie lines. The power of tie lines before and after optimization is shown in Fig. 2. The power of tie lines with high failure probability is significantly reduced. The value of branch active evaluation function is 248.65 before optimization and 71.86 after optimization. The value of evaluation function decreases significantly.

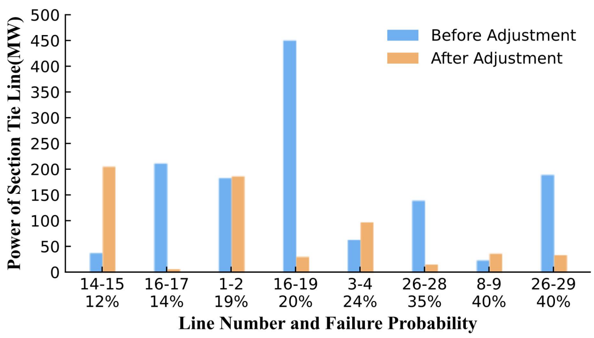

Figure 2. Power of Section Tie Lines

B. Collaborative restoration

It is assumed that after natural disasters, some transmission lines and communication equipment on the lines will be damaged, forming the blackout scenario as shown in Fig. 3.

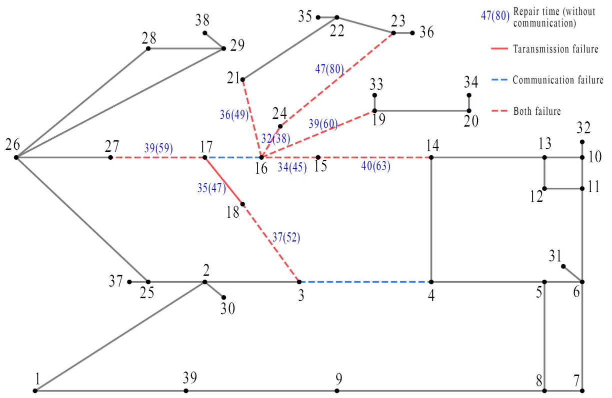

Figure 3. System Failure Scenario

Measurement and monitoring devices in the cyber physical system can provide information about line failures to estimate line repair time. The loss of cyber system not only increases the difficulty of repair, but also cannot estimate the repair time, so it can be expressed by the maximum repair time. The maintenance time of transmission line failure caused by disasters is positively correlated with line length and disaster intensity, and the length and strength can be reflected by line reactance and failure probability.

In this example, the recovery time is assumed as follows. There is a communication line repair team and a transmission line repair team, and they perform tasks at the same time. The repair time of communication line is 50 minutes, and the charging time of undamaged transmission line is 10 minutes. The repair and charging time of the damaged transmission line is related to the length and communication conditions. The line repair time is shown in Fig. 3, in which the number outside the bracket indicates the repair time with the assistance of communication, and the number in the bracket indicates the repair time in case of communication failure.

Using the proposed restoration optimization method to solve the above example, taking Δt for 1 minute, a coordinated restoration scheme for information and power equipment is obtained as shown in Tab. 1. Draw a resilience bi-evaluation curve as shown in Fig. 4, where the smaller the area enclosed by the curve and the zero-mark, the stronger the resilience. It can be seen that in the restoration process, the primary goal is to restore the lost load, which is faster than the equipment restoration. When the load restoration is completed, the goal is to restore the communication and transmission equipment.

TABLE I. COORDINATED RESTORATION SCHEME

Type	Line restoration scheme
Cyber	16-24 , 16-19 , 3-18 , 3-4 , 17-27 , 14-15 , 23-24 , 15-16 , 16-21 , 3-4 , 16-17
Electrical	16-21 , 15-16 , 16-24 , 16-19 , 3-18 , 3-4 , 16-17 , 17-18 , 17-27 , 14-15 , 23-24

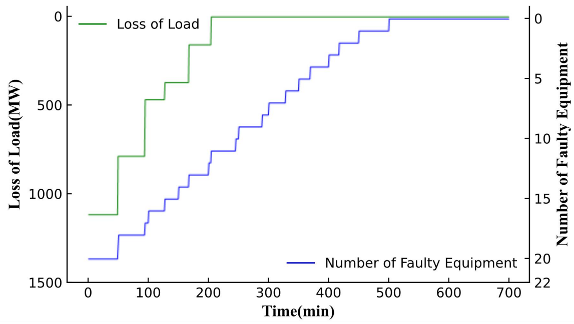

Figure 4. Double Evaluation Function

There are three scenarios to be considered in the restoration process: 1) the coordinated restoration of both transmission and communication equipment restoration sequence; 2) only the auxiliary restoration of the remaining available communication equipment for transmission line restoration; 3) the independent restoration without considering the auxiliary effect of communication equipment at all.Loss load curve and outage number curve of communication and transmission lines are plotted respectively, as shown in Fig. 5.The function evaluation values are shown in Tab. 2.

Comparing the data in the diagram, we can see that the coordinated restoration of cyber physical system can effectively improve the speed of system restoration, reduce the load loss caused by power outage, and accelerate the restoration of important lines to strengthen the grid structure.

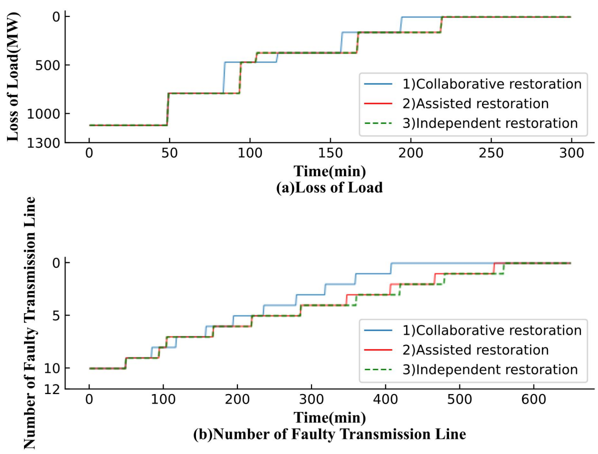

Figure 5. Comparison of Evaluation Functions for Different Situations

TABLE II. RESTORATION VALUE

	Collaborative Restoration	Assisted Restoration	Independent Restoration
Load restoration evaluation f_{ld}(MW·h)	118.24	126.26	126.26
Line restoration evaluation f_{eq}	21.99	26.83	27.35

V. Conclusion

To solve the problem that power system is vulnerable to extreme disasters, this paper proposes a three-stage strategy to enhance the resilience of cyber physical power system. The proposed zone division method and branch active power adjustment method can effectively reduce the risk of cascading failure or system instability caused by line fault disconnection in the disaster process. Compared with the case of information assisted restoration and independent restoration, the proposed collaborative restoration method can effectively accelerate the restoration speed of the cyber physical system. With the advantage of cyber physical system, the resilience of power system can be effectively improved.

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